Research on the Influence of Market Distortion of Deep-sea Equipment Supporting Industry on Digital Green Transformation in Hainan Province from the Perspective of Innovation Efficiency

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Abstract. Faced with economic shifts, Hainan's deep-sea equipment sector is crucial for regional prosperity, with digital and green advancements significantly impacting GDP growth. This study explores the factor market distortions that hinder industry transformation, affecting innovation and investment. The research finds that although digital green initiatives have positive economic potential, market distortions limit these benefits. This paper presents policy recommendations to optimize market factors, enhance innovation, and accelerate industry transformation to revitalize Hainan's economy.

Keywords: Innovation Efficiency, Market Distortion, Digital Advancement, Ecological Growth, Hainan Deep-Sea Support Industry.

1 Introduction

Hainan's deep-sea equipment industry plays a key role in driving the province's economic development and aligning with global marine conservation efforts. Over the past five years, the annual output value growth rate of Hainan's deep-sea equipment industry has been maintained at over 15%, significantly higher than the national average for similar industries (about 8%) and approaching the world's leading level (about 18%)[1]. This remarkable growth trend not only highlights Hainan's competitiveness in the field of deep-sea technology but also further consolidates the industry's important position in the regional economy. The 14th Five-Year Plan for Marine Economy has clarified the strategic direction of industrial innovation and integration. As climate challenges and resource shortages highlight the urgency of green manufacturing, Hainan has leveraged its marine resources and policy support to improve international competitiveness. This study systematically explores the impact of market distortions on innovation efficiency and industrial green transformation, aiming to provide policy insights for sustainable, high-quality development.

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2 Literature Review

Current research on the digital green transformation of the deep-sea equipment supporting industry in Hainan Province is still insufficient from the perspective of innovation efficiency, especially regarding the impact of factor market distortion on this field's transformation. Yu Huachen et al. show that factor market distortion significantly restricts the innovation efficiency of enterprises by affecting their R&D investment[2]. In Hainan's deep-sea equipment supporting industry, a similar phenomenon may also exist; when the price of factors is unreasonably low, enterprises may be more inclined to rely on low-cost traditional production factors rather than invest resources for technological innovation, thus hindering the industry's green process. The research of Wei Pengfei and Wei Xinyue further points out that resource misallocation caused by factor market distortion is one of the key factors inhibiting the improvement of total factor productivity[3]. This conclusion also has implications for Hainan's deep-sea equipment supporting industry, where market distortion may prevent resources from effectively flowing to the links most in need of innovation and technology upgrading, thus affecting the efficiency of the green transformation of the entire industry.

The study of Tian Zawa et al. revealed the impact of factor market distortion on the heterogeneity of green transformation efficiency and emphasized the importance of considering industry characteristics when formulating environmental regulation policies[4]. For Hainan's deep-sea equipment supporting industry, its unique industrial characteristics and technical needs mean that when promoting the digital green transformation, it is necessary to fully consider and respond to the challenges brought by factor market distortion and formulate targeted environmental regulatory policies and innovation incentives. Additionally, Wu Weixiang and Lin Shoufu's research pointed out that factor market distortions may lead to excessive concentration of resources in some traditional or mature industries, while emerging industries such as deep-sea equipment supporting industries may be hindered by a lack of resources, forming a low-end lock in the industrial structure[5]. This phenomenon is also worthy of vigilance in the process of green transformation of Hainan's deep-sea equipment supporting industry, which requires policymakers to provide strong support for the green development of emerging industries by deepening factor market reform and optimizing resource allocation[6].

Studies indicate factor market distortions negatively affect industry greening and innovation[7]. Future research on Hainan's deep-sea equipment should explore correction strategies for policy and market mechanisms to boost innovation and transformation.

3 Theoretical Foundations and Methodological Approach

3.1 Innovation Efficiency: A Core Metric

Innovation efficiency serves as a pivotal measure of an industry's capacity for innovation, reflecting the optimal use of resources in research and development endeavors. For Hainan's deep-sea equipment sector, enhancing this metric is crucial for navigating the complex marine environment and securing a competitive edge in the global marine economy[8].

3.2 Market Distortions: Hindrances to Equilibrium

The theory of factor market distortions highlights the impact of imperfect market mechanisms or policy interventions that cause a divergence between factor prices and their marginal product, leading to suboptimal resource allocation[9]. In Hainan, this manifests as shortages in skilled labor, insufficient R&D funding, and challenges in acquiring key technologies, impeding the industry's innovation and green transformation.

3.3 Digital and Green Synergy

The concept of digital green transformation underscores the integration of advanced digital technologies with eco-friendly practices to achieve resource efficiency and environmental sustainability[10]. For Hainan's industry, this involves leveraging digital tools to improve operational precision and safety while adopting green technologies to ensure sustainable marine resource development.

3.4 Interlinkages and Impacts

The interplay between innovation efficiency, market distortion, and digital green transformation is complex and two-way. Figure 1 below takes the deep-sea equipment supporting industry in Hainan Province as an example to visualize the relationship between innovation efficiency, factor market distortion and digital green transformation. Increased innovation efficiency drives digital green transformation, while market distortions can hinder this process by constraining innovation.

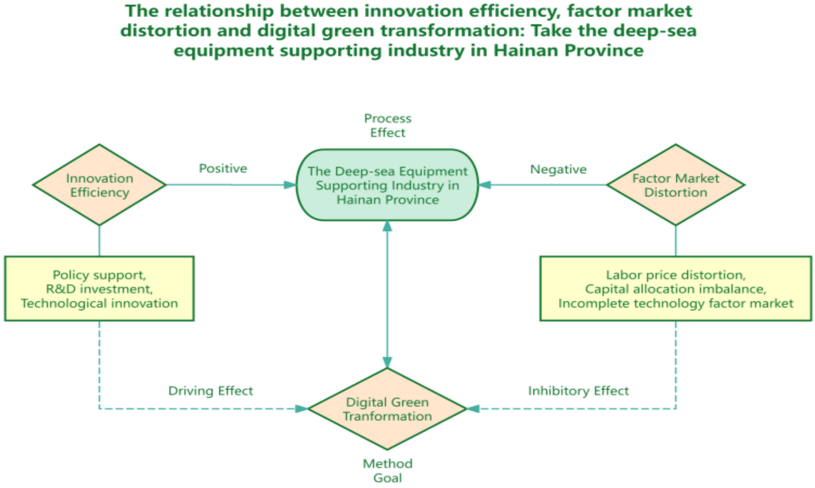

Fig. 1. The Relationship Between Innovation Efficiency, Factor Market Distortion and Digital Green Transformation: Take the Deep-sea Equipment Supporting Industry in Hainan Province

4 Status Analysis of Hainan's Deep-sea Equipment Supporting Industry

Driven by the national marine strategy, Hainan's deep-sea equipment industry has developed rapidly, becoming a key industry for high-quality economic growth and technological progress. Figure 2 below shows the added value of the Marine economic industry in Hainan Province during 2017-2022. From 2017 to 2022, the added value of the marine economy industry far exceeded the other six industries among Hainan Province's seven major industries, with the output value reaching 208.018 billion yuan in 2023[11]. At the same time, the proportion of output value brought by the marine economy industry to GDP showed a significant increase from 2017 to 2022, with the highest reaching 32.5% in 2020[12]. However, Industrial clusters face labor shortages and capital access hurdles, impeding innovation and green shifts. Sustainable development requires policy backing and government, business, and societal collaboration.

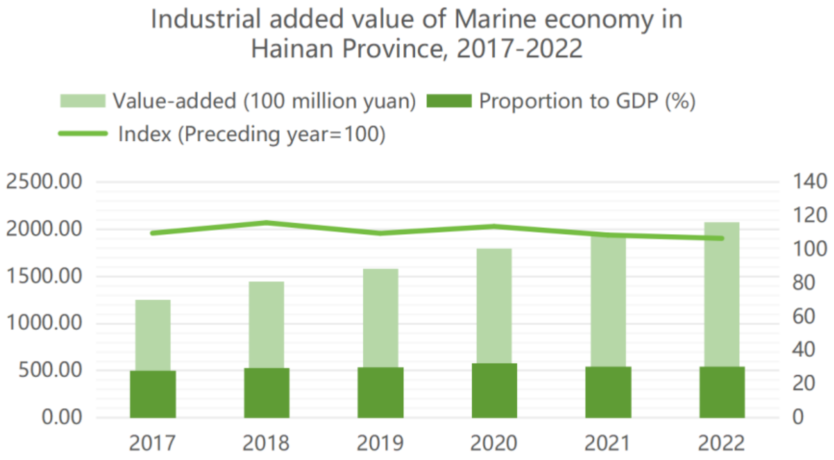

Fig. 2. Industrial Added Value of Marine Economy in Hainan Province, 2017-2022

5 Game Theory Model Setting and Analysis

5.1 Players and Strategies

In this evolutionary model, we consider two populations:

Government (G): Responsible for implementing policies.
Enterprises (E): Responsible for making investment decisions.
Government Strategies:
P: Implement incentive policies.
NP: Do not implement incentive policies.
Enterprise Strategies:
I: Invest in innovation.

NI: Do not invest in innovation.

5.2 Payoff Functions

The payoffs for the government and enterprises depend on the interaction of their strategies. These payoffs evolve over time as both the government and enterprises learn from the success or failure of their strategies.

Government Payoff (UG):

P, I: $U_G(P,I)=\alpha-c_g$ — High payoff due to successful policy outcomes.

P, NI: $U_G(P,NI)=\beta-c_g$ — Moderate payoff due to partial effectiveness.

NP,I: $U_G(NP,I)=\gamma$ — Moderate payoff due to successful innovation without government intervention.

NP, NI: $U_G(NP,NI)=\delta$ — Low payoff due to poor industry performance.

Enterprise Payoff (UE):

P, I: $U_E(P,I)=\pi-c_e+s$ — Highest payoff due to reduced innovation costs and increased returns.

P, NI: $U_E(P,NI)=\pi-c_e$ — Lower payoff even with government support.

NP, I: $U_E(NP,I)=\pi-c_e$ — Moderate payoff as enterprises bear the full cost of innovation.

NP, NI: $U_E(NP,NI)=\pi$ — Lowest payoff due to no innovation and no support.

Where:

$\alpha,\beta,\gamma,\delta$ are the payoffs for the government.

π is the baseline payoff for enterprises.

c_g and c_e represent the costs to the government and enterprises, respectively.

s is the subsidy provided under the incentive policy.

5.3 Evolutionary Dynamics

The dynamics of strategy evolution are modeled using replicator dynamics. These dynamics describe how the proportion of the population adopting each strategy changes over time, depending on the relative success of that strategy.

For the government population $x(t)$ adopting policy P, the dynamic equation is: $\dot{x}=x(t)\left[U_G(P)-\overline{U}_G\right]$

Where:

$x(t)$ is the proportion of the government population implementing incentive policies.

$\dot{x}(t)$ is the rate of change of $x(t)$.

$U_G(P)$ is the payoff for the government when implementing policies.

$\overline{U}_G = x(t)\cdot U_G(P)+[1-x(t)]\cdot U_G(NP)$ is the average payoff for the government population.

Substituting the payoffs:

$$\dot{x}(t)=x(t)[\alpha-c_g-(x(t)\cdot(\alpha-c_g)+(1-x(t))\cdot\gamma)]$$

Simplifying:

$$\dot{x}(t)=x(t)\cdot(1-x(t))\cdot(\alpha-\gamma-c_g)$$

This equation shows that the growth rate of the government strategy implementing incentive policies depends on the difference between the payoffs from implementing and not implementing policies. If $\alpha>\gamma+c_g$, the incentive policy implementation strategy will grow over time, leading to a higher proportion of governments adopting this strategy.

For the enterprise population $y(t)$ adopting strategy III, the dynamic equation is: $\dot{y}(t)=y(t)[U_E(I)-\overline{U}_E]$

Where:

$y(t)$ is the proportion of enterprises investing in innovation.

$\dot{y}(t)$ is the rate of change of $y(t)$.

$U_E(I)$ is the payoff for enterprises when investing in innovation.

$\overline{U}_E = y(t)\cdot U_E(I)+[1-y(t)]\cdot U_E(NI)$ is the average payoff for the enterprise population.

Substituting the payoffs:

$$\dot{y}(t)=y(t)[\pi-c_e+s-(y(t)\cdot(\pi-c_e+s)+(1-y(t))\cdot\pi)]$$

Simplifying:

$$\dot{y}(t)=y(t)\cdot(1-y(t))\cdot(s-c_e)$$

This equation indicates that the growth rate of the enterprise strategy investing in innovation depends on the difference between the subsidy provided and the cost of innovation. If $s>c_e$, the strategy of investing in innovation will spread among enterprises, leading to a higher proportion of enterprises adopting this strategy.

5.4 Fixed Points and Stability Analysis

To find the equilibrium points where the system stabilizes, we set $\dot{x}(t)=0$ and $\dot{y}(t)=0$. These conditions give us the fixed points, which indicate stable strategy profiles over time.

Government Equilibrium Condition: $U_G(P)=\overline{U}_G$

Enterprise Equilibrium Condition: $U_E(I)=\overline{U}_E$

By solving these equations, we identify the strategy combinations where no player has an incentive to unilaterally change their strategy, leading to a stable evolutionary equilibrium.

5.5 Evolutionary Stable Strategy (ESS)

For the P, I strategy to be an ESS, the following conditions must be met:

Condition 1:

The payoff for the government when implementing incentive policies must be greater than or equal to the payoff when not implementing policies: $\alpha - c_g \geq \gamma$ .This implies that the benefits of implementing policies must outweigh the costs for the government.

Condition 2:

The payoff for enterprises investing in innovation under the policy must be greater than or equal to the payoff when not investing: $\pi - c_e + s \geq \pi$. This simplifies to: $s \geq c_e$. The subsidy provided by the government must at least cover the cost of innovation for enterprises.

If both conditions are satisfied, the P, I strategy becomes evolutionarily stable, meaning it will persist in the population over time and resist invasion by other strategies.

According to the calculation and analysis results of the above evolutionary game theory, we summarize the government payment, firm reporting and stability conditions under different strategic combinations. Table 1 below illustrates the specific situation.

Table 1. Government Payment, Firm Reporting and Stability Conditions Under Different Strategic Combinations in Evolutionary Game Theory

Strategy Combination	Government Payoff	Enterprise Payoff	Condition for Stability
Gov: P, Ent: I	$\alpha - c_g$	$\pi - c_e + s$	$\alpha - c_g \geq \gamma$
Gov: P, Ent: NI	$\beta - c_g$	$\pi - c_e$	$\beta - c_g \geq \delta$
Gov: NP, Ent: I	γ	$\pi - c_e$	$s \geq c_e$
Gov: NP, Ent: NI	δ	π	$s < c_e$

6 Policy Implications

Based on the detailed analysis of the evolutionary dynamics, the following policy implications can be drawn:

6.1 Designing Effective Incentive Policies

The government should focus on designing incentive policies that provide sufficient subsidies (s) to cover or exceed the innovation costs (c_e). This ensures that enterprises find it profitable to invest in innovation, making the P, I strategy dominant[13].

6.2 Addressing Market Distortions

Market distortions that increase innovation costs (c_e) should be mitigated through targeted interventions. This can include improving access to affordable capital, reducing bureaucratic hurdles, and fostering a competitive market environment that encourages efficiency.

6.3 Ensuring Policy Consistency

Policy consistency is crucial for maintaining the stability of the P, I strategy. Frequent policy changes can lead to uncertainty, discouraging enterprises from investing in innovation. The government should provide a stable policy framework that supports long-term planning by enterprises.

6.4 Monitoring and Adapting Policies

The government should continuously monitor the effectiveness of its policies and adapt them as necessary to maintain the evolutionary stability of the P, I strategy. This includes adjusting subsidy levels, addressing emerging market distortions, and ensuring that the benefits of policies continue to outweigh the costs[14].

6.5 Promoting Collaboration and Innovation Ecosystems

The government can enhance the effectiveness of its policies by fostering collaboration among enterprises, research institutions, and other stakeholders. Creating innovation ecosystems that support knowledge sharing and technological advancement will further strengthen the P, I strategy.

7 Long-Term Strategic Planning

To sustain the growth and competitiveness of Hainan's deep-sea equipment industry, the government should focus on the following long-term strategies:

7.1 Investing in Research and Development Infrastructure

Developing state-of-the-art research facilities and innovation hubs will provide enterprises with the resources needed to innovate, reducing the reliance on government subsidies over time.

7.2 Encouraging International Partnerships

Engaging in international partnerships and knowledge exchange will help Hainan's deep-sea equipment industry stay at the forefront of technological advancements, ensuring it remains competitive on a global scale[15].

7.3 Building Human Capital

Investing in education and training programs that develop the necessary skills for innovation and technology adoption will ensure that the industry has access to a skilled workforce capable of driving growth.

8 Conclusion

The evolutionary game theory model provides a comprehensive framework for understanding how government policies and enterprise behaviors interact over time in Hainan's deep-sea equipment industry. By ensuring that the P, I strategy becomes an evolutionarily stable strategy, the government can promote sustained innovation and green transformation.

The detailed analysis highlights the importance of well-designed, consistent policies that provide sufficient incentives for enterprises to invest in innovation. Addressing market distortions, promoting collaboration, and investing in long-term strategic initiatives are crucial for ensuring the continued growth and competitiveness of Hainan's deep-sea equipment industry.

Future research should focus on empirically validating the model through case studies and data analysis, as well as exploring the impact of global trends and technological changes on the evolutionary dynamics in this sector.

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